KUNS-1640

Self-Regulation of Star Formation in Low Metallicity Clouds

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ABSTRACT

We investigate the process of self-regulated star formation via photodissociation of hydrogen molecules in low metallicity clouds. We evaluate the influence region's scale of a massive star in low metallicity gas clouds whose temperatures are between 10^2 and 10^4 Kelvin. A single O star can photodissociate H_2 in the whole of the host cloud. If metallicity is smaller than about $10^{-2.5}$ of the solar metallicity, the depletion of coolant of the the host cloud is very serious so that the cloud cannot cool in a free-fall time, and subsequent star formation is almost quenched. On the contrary, if metallicity is larger than about $10^{-1.5}$ of the solar metallicity, star formation regulation via photodissociation is not efficient. The typical metallicity when this transition occurs is $\sim 10^{-2}$ of the solar metallicity. This indicates that stars do not form efficiently before the metallicity becomes larger than about 10^{-2} of the solar metallicity and we considered that this value becomes the lower limit of the metallicity of luminous objects such as galaxies.

Subject headings: cosmology: theory — early universe — galaxies: formation — H II region — ISM: clouds — stars: formation

1. Introduction

After the recombination era, little information is accessible until $z \sim 5$, after that we can observe objects such as galaxies and QSOs. On the other hand, the reionization of the intergalactic medium and the presence of heavy elements at high-z suggest that there are other populations of luminous objects, which precedes normal galaxies. Thus, a theoretical approach to reveal the formation mechanism of such unseen luminous objects is very important.

The formation process of a luminous object is roughly divided into three steps, formation of cold clouds by H and/or H_2 line cooling, formation of the first generation stars in the cold clouds, and the star formation throughout the clouds. However, the mass of the first generation stars are estimated through detailed investigation to be fairly large (Nakamura & Umemura 1999, Omukai & Nishi 1998). Thus, the third step is disturbed by the feedback from the massive stars formed in the clouds. The main feedback consists of two different processes, UV radiation from the stars and energy input by supernovae (SNe). Through ionization of H (Lin & Murray 1992) and dissociation of H_2 (Silk 1977, Omukai & Nishi 1999), ultra violet (UV) radiation has negative feedback on further star formation in the host clouds. Especially, H_2 is dissociated in such a large region that the whole of ordinary low mass cosmological object is influenced by one O5 type star (Omukai & Nishi 1999). For the case of a metal-free gas cloud, the influence region is much wider than the HII region and the metal-free host cloud lacks coolant and cannot cool. Thus, next generation stars are hardly formed before the first generation stars die. However, the life time of massive stars is much shorter than the cosmological time scale and they die as SNe. By these SN explosions, the cloud's gas is often dispersed before significant amount of total gas is transformed in stars (e.g., Mac Low & Ferrara 1999, Ciardi et al. 1999, Nishi & Susa 1999). On the other hand, if the gas binding is not disrupted, next generation stars are formed in a cloud which is slightly polluted by heavy elements. Even in the case that the host cloud is disrupted by SN explosions, if the remnant gas does not escape from the host pregalactic object, next generation clouds, which is slightly polluted, will be formed and subsequent star formation will follow. In these polluted clouds, heavy elements will become important coolants, if their abundances increase to some degree. After the host cloud is enough polluted that star formation regulation by UV radiation is not efficient, the effective star formation can start. Thus, the pregalactic object, which is a cloud complex will evolve into a luminous object such as galaxy.

In this paper, we investigate the self regulation of star formation via UV radiation, and assess the critical metallicity which enables the formation of luminous objects.

2. Influence Region of a Massive Star in a Low Metallicity Cloud

Around an OB star, hydrogen is photoionized, and an HII region is formed. Lin & Murray (1992) considered the star formation regulation via photoionization. However, the regulation can be efficient outside the HII region via photodissociation of H_2 in a low metallicity cloud, where H_2 line emissions are the most important coolant.

Although ionizing photons hardly escape from the HII region, photons whose radiation energy are below the Lyman limit can get away. Such UV photons photodissociate H_2, and a photodissociation region (PDR) is formed around the HII region. In a PDR in a metal-free cloud, H_2 dissociation effect is very efficient so that the region which is larger than the whole of cosmological low mass cloud is influenced by only one O5 type star (Omukai & Nishi 1999). However, after a cloud is polluted by heavy elements, the situation becomes complicated, since other thermal processes may be important in a PDR in a cloud with heavy elements. In the region, CO molecules are dissociated also, since the threshold UV energy of H_2 and CO dissociation are close, and C, Si and Fe in the gas phase are ionized, since ionizing energies of C, Si and Fe are lower than H. Thus, C^+, Si^+ and Fe^+ cooperate with H_2 as main coolants in a low metallicity cloud. On the other hand, dust photoelectric heating becomes important heating source in a polluted cloud. In this section, we study how much mass in a low metallicity cloud is affected by UV photons from an OB star and, as a result, becomes unable to cool in a free-fall time.

To calculate the heating rate (Γ) and the cooling rate (Λ) per unit volume, we use the rates of Wolfire et al. (1995) and the references there in, and the rates of Galli & Palla (1999) (processes related to H_2). But we do not include the effects of X-ray and cosmic ray. We assume the ionization degree x_e as

$$x_e = x_{\rm H^+} + x_{\rm C^+} + x_{\rm Si^+} + x_{\rm Fe^+}, \tag{1}$$

where x_i is the abundance of the i element. We assume that abundances of heavy elements are determined from the cosmic abundances by scaling proportional to $z/z_\odot$[1]. The adoptive values are $x_{\rm C} = 10^{-3.52} z/z_\odot$, $x_{\rm O} = 10^{-3.34} z/z_\odot$, $x_{\rm Si} = 10^{-5.45} z/z_\odot$ and $x_{\rm Fe} = 10^{-6.15} z/z_\odot$. We assume that all of these elements are ionized. Here we add the extra term $x_{\rm H^+}$ to evaluate the effect of relic ionization of cosmological recombination and/or previous SN, etc.. We investigate for the cases of $x_{\rm H^+} = 10^{-4}$ and $x_{\rm H^+} = 0$. However, the overall tendency is not affected by the value of $x_{\rm H^+}$. Thus, hereafter, we show the results for the case of $x_{\rm H^+} = 10^{-4}$ mainly. In a PDR, H_2 molecules

[1]The depletion of the gas phase abundance of heavy elements is serious in the interstellar clouds. However, the main coolant except H_2 is C^+ and O, and the depletion of C and O is not so large. Moreover, the depletion of C may not be serious considering dust formation in SN ejecta (e.g., Kozasa et al. 1989). But it may be possible that the depletion of C and O is more significant than the above estimate. In this case, we should consider that the gas phase abundances of C and O represent the heavy element abundance, and hence main results in this paper are almost the same.

are dissociated mainly via the two-step photodissociation process by the Lyman and Werner (LW) bands photons. For H_2 number density, we use the equilibrium value with the initial ionization degree (Omukai & Nishi 1999). This treatment may result in overestimation of x_{H_2} hence in overestimation of cooling rate (see e.g., Nishi & Susa 1999). However, to seek the lower bound of the region affected by the photodissociating UV radiation from a massive star, we use the equilibrium value.

H_2 is formed mainly via the H^- process

$$\begin{aligned} \mathrm{H} + e^- &\rightarrow \mathrm{H}^- + \gamma &(2)\\ \mathrm{H} + \mathrm{H}^- &\rightarrow \mathrm{H}_2 + e^-. &(3) \end{aligned}$$

The rate-determining stage of the H^- process is the reaction (2), whose rate coefficient k_{H^-} is (de Jeng 1972)

$$k_{\mathrm{H}^-} = 1.0 \times 10^{-18} T \ \mathrm{s}^{-1}\mathrm{cm}^3. \tag{4}$$

In a PDR, H_2 is dissociated mainly via the two-step photodissociation process

$$\mathrm{H}_2 + \gamma \rightarrow \mathrm{H}_2^* \rightarrow 2\mathrm{H}, \tag{5}$$

where rate coefficient k_{2step} is given by (Kepner et al. 1989, Draine and Betoldi 1996)

$$k_{\mathrm{2step}} = 1.13 \times 10^8 F_{\mathrm{LW}} \ \mathrm{s}^{-1}. \tag{6}$$

Here F_{LW} (ergs $\mathrm{s}^{-1}\mathrm{cm}^{-2}\mathrm{Hz}^{-1}$) is the averaged radiation flux in the Lyman and Werner (LW) bands. Thus, the equilibrium number density of H_2 under ionization degree x_e is

$$\begin{aligned} n_{\mathrm{H}_2} &= \frac{k_{\mathrm{H}^-}}{k_{\mathrm{2step}}} x_e n_{\mathrm{H}}^2 \\ &= 0.88 \times 10^{-26} x_e F_{\mathrm{LW}}^{-1} T n_{\mathrm{H}}^2, \end{aligned} \tag{7}$$

where n_{H} is the number density of the Hydrogen nuclei. On the other hand, the averaged flux in the Lyman and Werner bands is approximately given by

$$F_{\mathrm{LW}} = \frac{L_{\mathrm{LW}}}{4\pi r^2}. \tag{8}$$

Then, if self shielding effect can be neglected, n_{H_2} is proportional to r^2 and only at the very outer region, x_{H_2} becomes abundant enough for efficient cooling.

However, self shielding effect is important for ordinary clouds considered in this paper. If column density of H_2 becomes larger than 10^{14} cm^{-2}, F_{LW} decreases because of self shielding (Draine and Betoldi 1996). At the outer region where LW band radiation is shielded, H_2 is dissociated via thermal collision and n_{H_2} becomes thermal equilibrium value. In this case, H_2 is the more abundant if the temperature is the lower.

Figure 1 shows the change of cooling and heating rates per unit volume (Λ and Γ) with the distance from the central massive star for the typical cloud ($n = 10$ cm^{-3},

$T = 3000$ K). Here we have assumed the existence of one O5 star, whose mass is $\sim 40\ M_\odot$ and luminosity of the LW bands is $\sim 10^{24}$ ergs s^{-1} Hz^{-1} [2], at the center of the cloud, and also assumed n, T and x_e are constant in space, for simplicity. At the inner region where LW band radiation is not shielded, OI and CII line cooling is the dominant cooling process, and hence the cooling rate is approximately proportional to z. On the other hand, at the outer region where LW band radiation is shielded, H_2 line cooling becomes dominant for metal poor clouds.

We calculate the cooling time

$$t_{\rm cool} = \frac{(3/2)nkT}{\Lambda_{\rm eff}}, \tag{9}$$

where n and T are the number density and the temperature of the cloud and $\Lambda_{\rm eff}$ $(\equiv \Lambda - \Gamma)$ is the effective cooling rate. Figure 2 shows the change of the cooling time with the distance from the center.

If metallicity is slightly high ($z/z_\odot \gtrsim 10^{-2}$), the cooling time is shorter than the free-fall time $t_{\rm ff}$ $(\equiv (\frac{3\pi}{32G\mu m_{\rm H} n})^{1/2} \simeq 1.5 \times 10^7$ yr $(n/10\ {\rm cm}^{-3})^{-1/2})$ at the all region. Here G is the gravitational constant, μ is the mean atomic weight and $m_{\rm H}$ is the hydrogen mass. Considering HI region, almost all Hydrogen is atomic and $\mu \simeq 1.4$. On the contrary, if metallicity is very low, $t_{\rm ff} < t_{\rm cool}$ at the inner region and $t_{\rm ff} > t_{\rm cool}$ at the outer region. For the low density ($n \sim 1{\rm cm}^{-3}$) and high metallicity ($z/z_\odot \sim 1$) case, there exists no cool region where net cooling is negative (heating occurs) at the inner region.

For all cases shown in Fig. 2, $t_{\rm cool} < t_{\rm ff}$ is achieved at the region outer than a certain distance from the center, and we call this transition radius as the cooling radius ($r_{\rm cool}$). However, in the cases of $z/z_\odot = 10^{-1}$ and 1, the Strömgren radius, $r_{\rm S}$, is larger than $r_{\rm cool}$. If $r < r_{\rm S}$, the gas is fully ionized and the temperature becomes high, star formation is strongly suppressed. Thus, we take as actual $r_{\rm cool}$ the largest between $r_{\rm cool}$ and $r_{\rm S}$. In a region $r \le r_{\rm cool}$, next generation stars are hardly formed before the death of the central star, since cooling is inefficient ($t_{\rm cool} > t_{\rm ff}$). Thus, we consider this region as a influence region. For the very lower metallicity case, $z/z_\odot \lesssim 10^{-2.5}$, $r_{\rm cool}$ depends on z very weakly, since main coolant becomes H_2 at the outer region. If we adopt $x_{\rm H^+} = 0$, $n_{\rm H_2}$ depends a little on z so that the influence radius depends a little on z. But the overall tendency does not change from the case of $x_{\rm H^+} = 10^{-4}$.

The Strömgren radius is

$$r_{\rm S} \simeq 24{\rm pc}\ \left(\frac{n_{\rm H}}{10\ {\rm cm}^{-3}}\right)^{-2/3} \left(\frac{Q_*}{5.1 \times 10^{49} {\rm s}^{-1}}\right)^{1/3}, \tag{10}$$

[2]Note that although the total luminosity of a star depends strongly on the mass, the dependence of the luminosity in the LW bands depends is rather weak.

where Q_* is the flux of ionizing photons by a OB star and $Q_* \simeq 5.1 \times 10^{49}\mathrm{s}^{-1}$ for an O5 star. The mass within r_S is

$$M_\mathrm{s} \simeq 2 \times 10^4 M_\odot \left(\frac{n_\mathrm{H}}{10\ \mathrm{cm}^{-3}}\right)^{-1} \left(\frac{Q_*}{5.1 \times 10^{49}\mathrm{s}^{-1}}\right). \tag{11}$$

M_s is somewhat smaller than the typical cloud Jeans mass (see Figs. 3-5). Note that r_S and Q_* depend strongly on the mass of the central star. Thus, if we consider a less massive central star ($M \simeq 10 M_\odot$), r_s becomes much smaller but other features of these figures hardly change.

For some cases, especially for the high temperature and very low metallicity case, t_cool can not be shorter than t_ff for any distance case because of the insufficiency of x_{H_2}. In this case, r_cool is estimated to be ∞.

3. Star Formation Regulation in Low Metallicity Clouds

To evaluate the strength of the star formation regulation, we calculate the ratio of the cooling radius to the Jeans length, $r_\mathrm{cool}/r_\mathrm{J}$, in the n-T plane for the clouds with various metallicity ($0 \leq z/z_\odot \leq 1$). Here, $r_\mathrm{J} \equiv (\frac{\pi k T}{G\mu m_\mathrm{H}\rho})^{1/2} \simeq 2.1 \times 10^2 \mathrm{pc}(T/3000\ \mathrm{K})^{1/2}(n/10\ \mathrm{cm}^{-3})^{-1/2}$. As shown in Fig. 3, for the case of $z/z_\odot = 10^{-2}$, n-T plane is divided into two regions. In the region with higher density and/or lower temperature, $r_\mathrm{cool}/r_\mathrm{J}$ is smaller than unity. In other word, influence radius of a massive star is smaller than the typical scale of the cloud (r_J). Thus, the regulation is considered to be ineffective. In the other region, $r_\mathrm{cool}/r_\mathrm{J} > 1$ and the regulation works well. For dense clouds, in the right lightly shaded region, $t_\mathrm{cool} < t_\mathrm{ff}$ for the whole HI region. In this case, $r_\mathrm{cool} = r_\mathrm{S} \ll r_\mathrm{J}$. For low density and high temperature clouds, in the upper left shaded region, $t_\mathrm{cool} > t_\mathrm{ff}$ for the whole HI region. In this case, $r_\mathrm{cool} \gg r_\mathrm{J}$.

Figure 4 shows $r_\mathrm{cool}/r_\mathrm{J}$ on the n-T plane, for the case of $z/z_\odot = 10^{-1.5}$. In this case $r_\mathrm{cool}/r_\mathrm{J} < 1$ for almost the whole region. Thus, star formation regulation by UV radiation is inefficient. On the contrary, as shown in Fig. 5, for the case of $z/z_\odot = 10^{-2.5}$, $r_\mathrm{cool}/r_\mathrm{J} > 1$ for almost the whole region and the regulation works very well. The transition occurs when the metallicity is $10^{-2.5} \lesssim z/z_\odot \lesssim 10^{-1.5}$, and the typical metallicity when the transition occurs is estimated as $z/z_\odot \simeq 10^{-2}$.

For the extremely low-metallicity case ($z/z_\odot \lesssim 10^{-4}$), the effect of heavy elements on the thermal process is almost negligible. Thus, considering the thermal process, it is difficult to distinguish a cloud with $z/z_\odot \lesssim 10^{-4}$ from a cloud with $z/z_\odot = 0$.

4. Discussion

For the primordial gas clouds, if we consider the self-shielding effect, the mass within the region of influence is obtained as (Omukai & Nishi 1999)

$$M^{(\mathrm{inf})} = 8 \times 10^6 M_\odot \left(\frac{x_\mathrm{e}}{10^{-4}}\right)^{-1} \left(\frac{L_\mathrm{LW}}{10^{24}\mathrm{ergs\ s^{-1}Hz^{-1}}}\right) \left(\frac{T}{3\times 10^3\mathrm{K}}\right)^{-1} \left(\frac{n}{10\mathrm{cm^{-3}}}\right)^{-1}. \tag{12}$$

This mass is larger than the typical cloud mass (see Fig. 3-5). On the contrary, for the low metallicity gas clouds, the strength of the self-regulation changes with the metallicity.

As shown in the previous section, in the case of very low metallicity clouds ($z/z_\odot \lesssim 10^{-2.5}$), star formation regulation by UV radiation is very effective. In this case, star formation rate is very low, since only one massive star can stop the evolution of the whole host cloud. If SNe do not disrupt the gas binding, the host cloud is polluted by heavy elements little by little and the following continuous star formation is possible. Even in the case that the host cloud is disrupted by SN explosions, if the remnant gas does not escape from the host pregalactic object, next generation clouds, which are slightly polluted, will be formed and subsequent star formation will follows. After metallicity becomes high enough ($z/z_\odot \gtrsim 10^{-2}$), effective star formation can start. Thus, the lower limit of metallicity of luminous objects is roughly estimated at $z/z_\odot \sim 10^{-2}$. By the way, a SN release several $\times M_\odot$ of heavy elements and the typical cloud mass ($\sim \rho r_\mathrm{J}^3$) is $\sim 10^6\ M_\odot$. Thus, if we consider that the cloud mass is $10^6\ M_\odot$ and the mass of the heavy elements released by one SN is $4M_\odot$, the metallicity increase per one SN is $\sim 4 \times 10^{-6}$ and the change of the metallicity is $\sim 2 \times 10^{-4} z_\odot$, and hence before efficient star formation begins, about 50 cycles of star formation and SN explosion is required. This implies that at the effective star formation epoch, there should exist some amount of heavy elements and dust and they are scattered well. Then, it is expected that it is hard for Ly α photons to escape from the clouds. Moreover, the inefficiency of star formation in low metallicity clouds may explain the G dwarf problem (e.g., Rocha-Pinto & Maciel 1996) and may also result in that the reionization epoch of the universe may become later than the previous studies (e.g., Fukugita & Kawasaki 1994, Haiman & Loeb 1997, Gnedin & Ostriker 1997).

The lifetime of very massive stars is $\sim 3 \times 10^6$ yr. However, as noted above, the mass dependence of the luminosity in the LW bands is rather weak, and hence even if the mass of the central star is smaller ($\lesssim 10\ M_\odot$), in this case the lifetime of the star is longer, star formation regulation can be efficient. Moreover, these less massive stars may not evolve into type II SNe. Thus, after the death of the first OB star, star formation could occur somewhere in the cloud, and another OB star could form successively. Therefore, star formation regulation becomes often serious even for clouds whose t_ff is longer than $\sim 3 \times 10^6$ yr.

Lin & Murray (1992) considered the regulation only via photoionization. In such a case, the affected region by an OB star becomes the region within a Strömgren sphere. For the very lower metallicity case, $r_{\rm S}$ is somewhat smaller than $r_{\rm cool}$. However, if metallicity is fairly high $z/z_{\odot} \gtrsim 10^{-1.5}$, $r_{\rm cool}$ becomes $r_{\rm S}$ for almost the whole region in n-T plane (see lightly shaded region in Fig. 4). Thus, for the higher metallicity case ($z/z_{\odot} \gtrsim 10^{-1.5}$), it is good approximation to consider that star formation regulation occurs only via photoionization, but in this case influence region is much smaller than the host cloud hence the regulation is not effective.

Recently, it has been shown that earlier phase of the chemical evolution of the Galaxy can be explained by the models with the assumption that SN-induced star formation is the only star formation process (e.g., Tsujimoto et al. 1999, Ishimaru & Wanajo 1999). As shown above, when the metallicity is lower ($z/z_{\odot} \lesssim 10^{-2}$), star formation can occur only after previous massive stars have died. If these massive stars dye with SN explosion, we can consider that SN-induced star formation is the only star formation process, since stars can form only after SN explosion.

We would like to thank H. Sato and anonymous referee for valuable comments. This work is supported in part by the Grant-in-Aid for Scientific Research on Priority Areas (No. 10147105) of the Ministry of Education, Science, Sports and Culture of Japan (RN).

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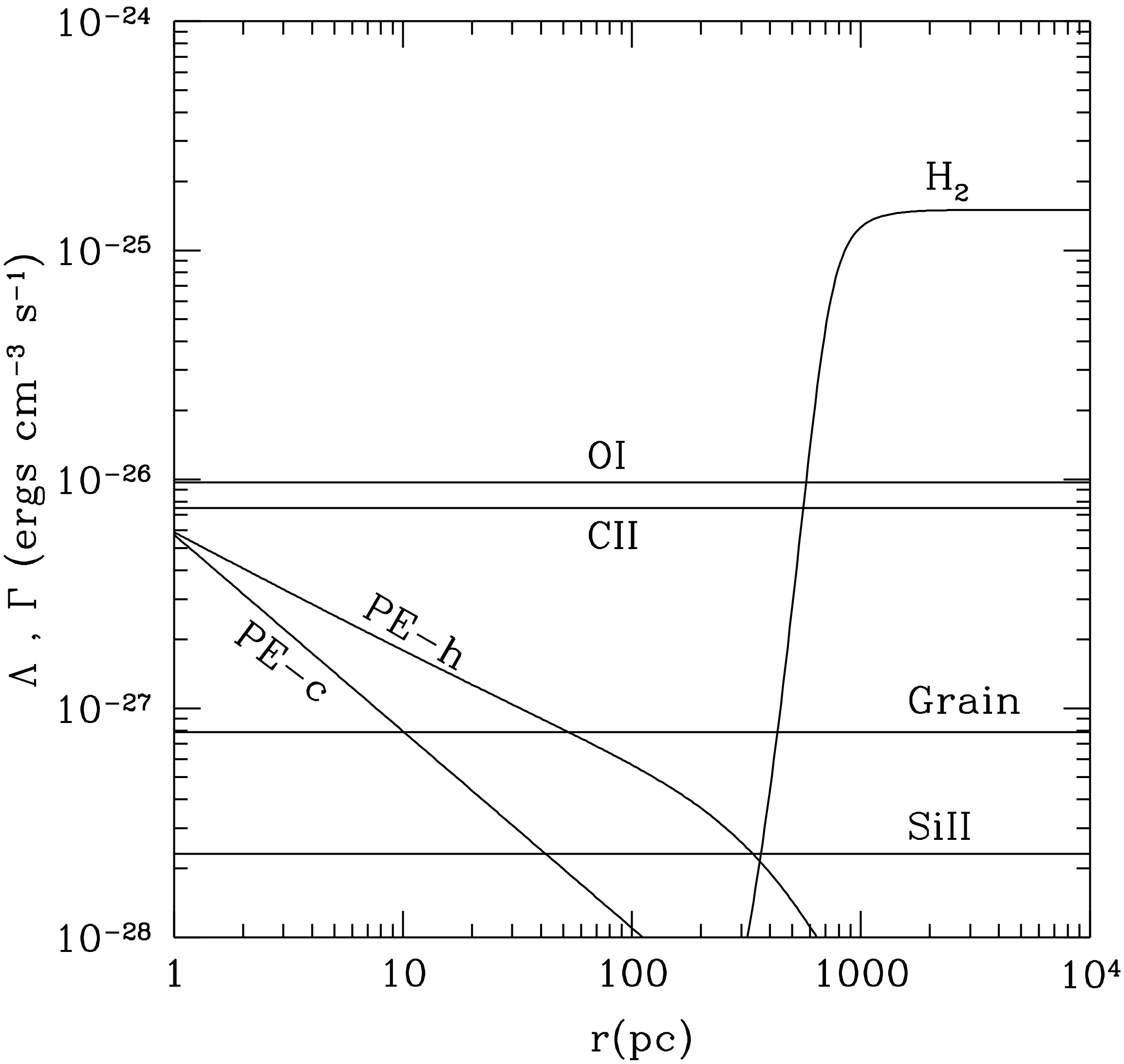

Fig. 1.— Change of the cooling and heating rates per unit volume (Λ and Γ) with the distance from the central massive star for the typical cloud (n = 10 cm^{-3}, T = 3000 K and $z = 10^{-2} z_{\odot}$). The central star is assumed to be one O5 star. PE-h and PE-c in the figure denote the grain photoelectric heating and cooling rates, respectively. The others denote radiative cooling rates of H_2, OI, CII, SiII and Grain, respectively.

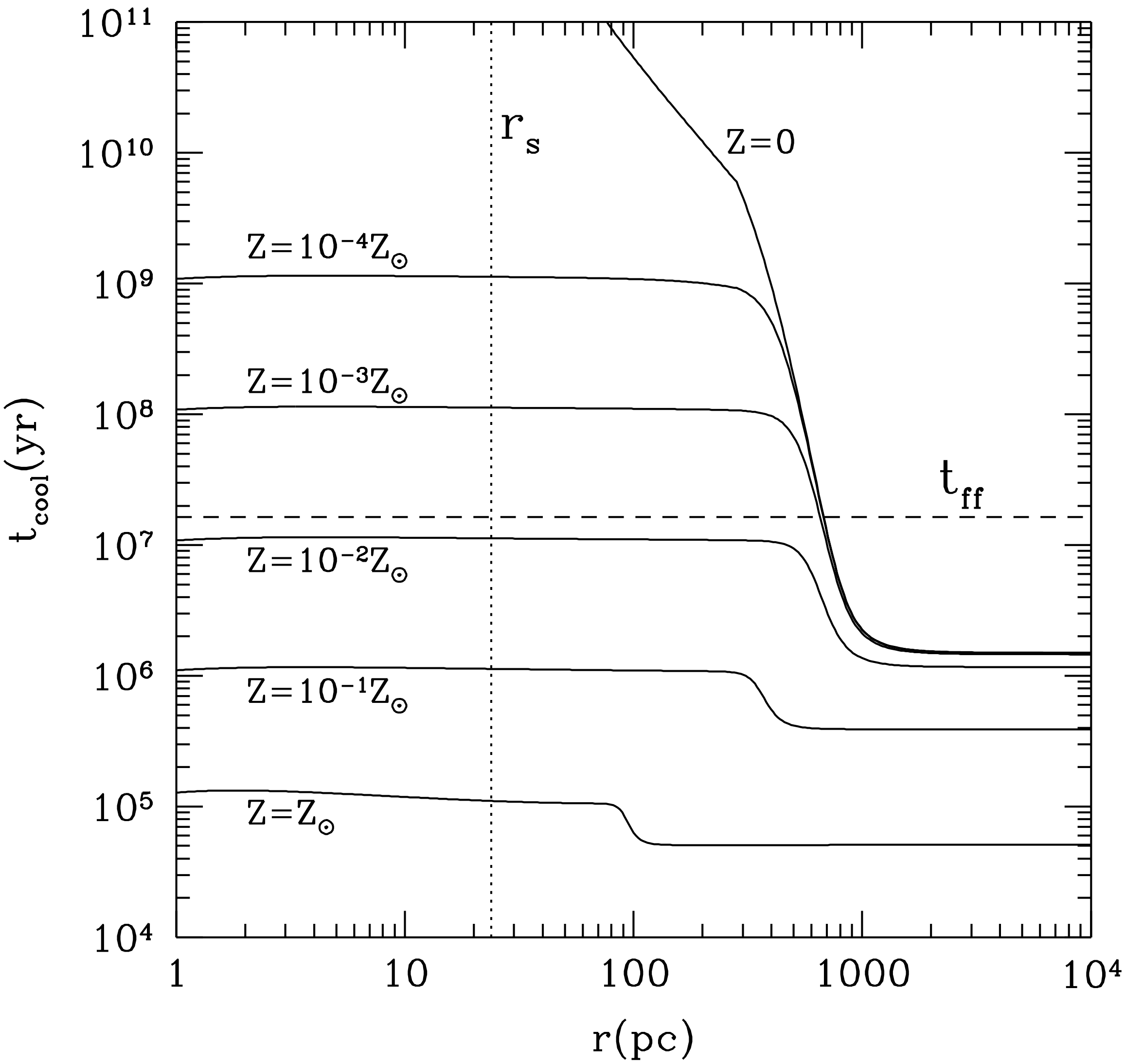

Fig. 2.— Cooling time $t_{\rm cool}$ at the various distance from the center for the typical cloud (n = 10 cm^{-3} and T = 3000 K). The metallicity is $z/z_{\odot}$ = 0, 10^{-4}, 10^{-3}, 10^{-2}, 10^{-1} and 1. The dotted line denotes the Strömgren radius, $r_{\rm S}$ for a O5 star. The dashed line denotes the free-fall time, $t_{\rm ff}$.

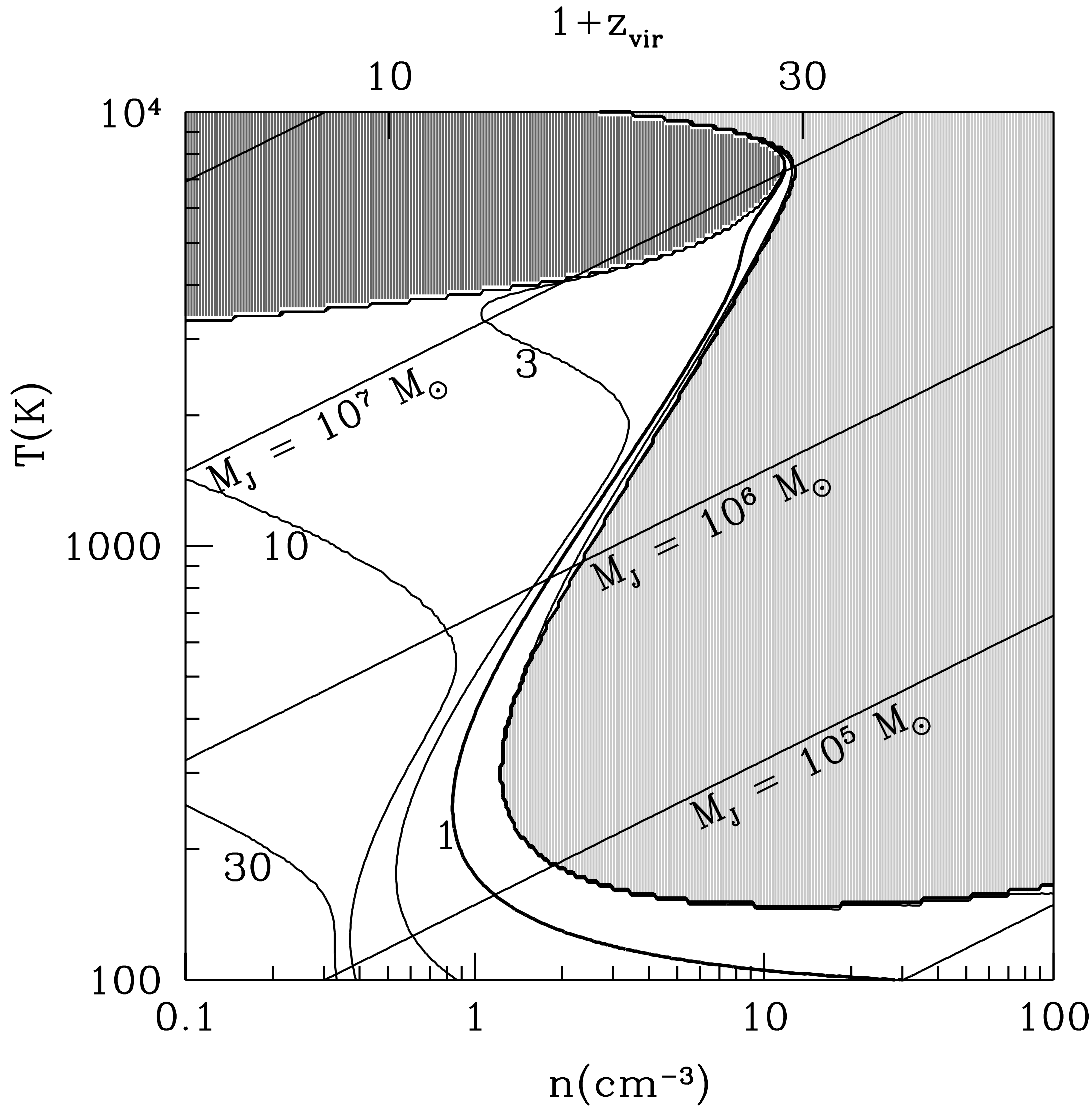

Fig. 3.— The ratio of the cooling radius to the Jeans length $r_{\rm cool}/r_{\rm J}$ for the case of $z/z_{\odot} = 10^{-2}$. The numbers in the figure denote the value of $r_{\rm cool}/r_{\rm J}$ of the contour. For dense cloud, in the right lightly shaded region, $t_{\rm cool} < t_{\rm ff}$ for the whole HI region. In this case, $r_{\rm cool} = r_{\rm S} \ll r_{\rm J}$. For low density and high temperature cloud, in the upper left shaded region, $t_{\rm cool} > t_{\rm ff}$ for the whole HI region. In this case, $r_{\rm cool} \gg r_{\rm J}$. The values of the Jeans mass are also shown. For reference, considering the cosmological objects, related virialized redshift is also shown on the upper axis for the flat universe with $\Omega_b = 1$.

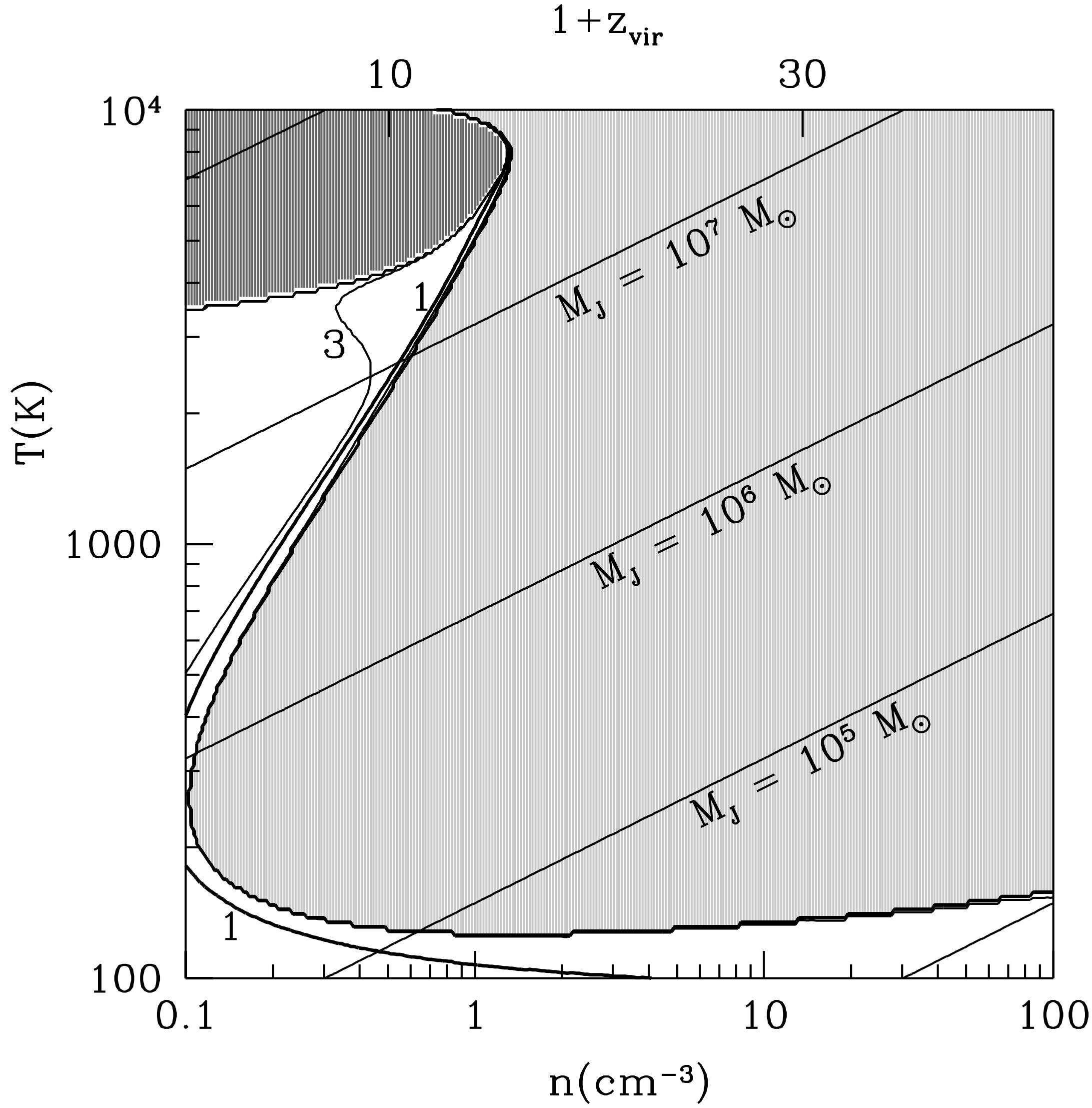

Fig. 4.— The same figure of Fig. 3 but for the case of $z/z_{\odot} = 10^{-1.5}$.

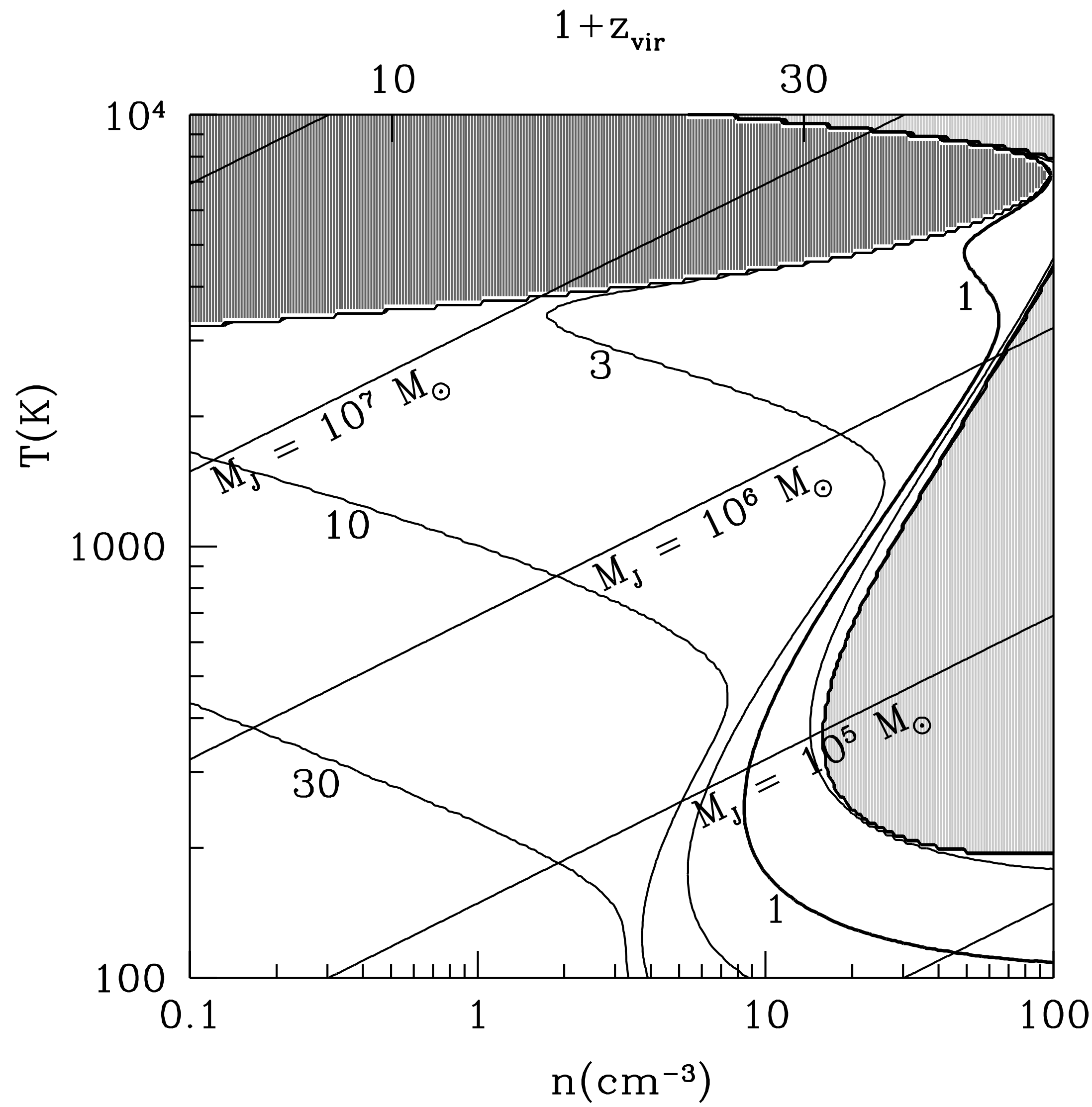

Fig. 5.— The same figure of Fig. 3 but for the case of $z/z_{\odot} = 10^{-2.5}$.